



Sizing the prime mover of a residential micro-combined cooling heating and power (CCHP) system by multi-criteria sizing method for different climates



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ABSTRACT

In the present study, a multi-criteria sizing function (MCSF) is proposed for designing the optimum size and operating strategy of the prime mover of a residential micro-combined cooling heating and power (CCHP) system. The CCHP prepares the electrical, thermal, cooling, and domestic hot water demands of the same building in five different climates in Iran. The MCSF integrates fuel energy saving ratio (FESR) and exergy efficiency as the thermodynamical parameters, net present value, internal rate of return and payback period for the economical criteria, and CO₂, CO and NO_x reduction for the environmental evaluations. Analytical hierarchy process is used to weigh each criterion with respect to others. The engine proposed by MCSF results in considerable fuel saving and pollution reduction and a payback period of about 6 years for the 5 climates. In addition, the best strategy according to the engine size is determined for every climate.

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1. Introduction

A combined cooling heating and power (CCHP) system produces power and uses the waste heat for cooling and heating purposes. With respect to the conventional systems of cooling, heating and power generation, the CCHP systems save energy, make economical revenue, and reduce environmental pollution. They also have higher safety in crises such as war or earthquake, and flexibility to be on-grid or off-grid [1–6].

Main components of a CCHP system comprise of the prime mover, the heat exchangers for the heating purpose, thermally activated cooling system, control system and the energy resource used. A heat storage system may be used occasionally for storing the extra heat to be used in the heating or cooling energy peak hours. The prime mover can be a gas turbine, reciprocating internal combustion engine, Stirling engine, steam turbine, micro gas or steam turbine and fuel cells. The thermally activated cooling system may include technologies such as absorption chiller, adsorption chillers, ejector refrigeration system and desiccant dehumidifiers. A

compression chiller may be used in addition to the thermally activated systems [1,5,7–11].

The prime mover size of the CCHP cycle tells us what strategy is used to provide the electricity or heat demand of the building. In the literature, three strategies are usually introduced. They are as follow [12–18]:

- 1 Following electrical load (FEL): In this strategy, the prime mover nominal size (E_{nom}) equals the electrical peak demand (E_{dem}) and no electricity is bought from the grid.
- 2 Following thermal load (FTL): In this case, the recovered heat (Q_{rec}) from the CCHP cycle is the same as the peak heat demand (Q_{dem}) and no auxiliary boiler is used.
- 3 Following seasonal strategy (FSS) or hybrid electric thermal system (HETS): in this strategy a load ratio (LR) is calculated monthly and if $LR > 1$ the FEL is used otherwise FTL should be used.

$$LR = \frac{\text{Monthly } E_{dem}}{\text{Monthly } Q_{dem}} \quad (1)$$

Although the numerical calculations show that, the third strategy is more efficient [12] but in practice, the third strategy is meaningless for residential buildings because it is impossible to use a single prime mover for both of the FEL and FTL and switch between them monthly. The reason is that the size of the prime mover for the FEL and FTL strategies is very different for the residential building applications. In addition, if we try to use the third strategy,

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Nomenclature			
AHP	Analytic hierarchy process	IC	Internal combustion engine
amb	Ambient	ii	Initial investment of components (Rial)
ATD	Aggregated thermal demand	I_{OM}	Operation and maintenance cost (\$/kW)
ATD'	The aggregated cooling and heating produced by sources other than engine recovered heat (kW)	IRR	Internal rate of return (%)
b	Boiler	$j = 0, 1$	CSP and CCHP as superscript
C	Cooling load (kW)	max	maximum
C'	The cooling produced due to the heat of auxiliary boiler (kW)	N	Normalized
C_1, C_2 and C_3	Thermodynamical, economical, and environmental criteria	nom	Nominal
CCHP	Combined cooling heating and power	NPV	Net present value (Rial)
cf	Cash flow (Rial)	P	Power or electricity (kW)
COP_{abc}	Coefficient of performance of the absorption chiller	PB	Payback period (year)
CSP	Conventional separate production	PHR	Power to heat ratio
D	Hot water demand load (kW)	PVP	Present value percentage
DHW	Domestic hot water	pp	Power plant as sub.
db	Dry bulb	Q	Heat (kW)
dem	Demand of building	r	Interest rate (%), and recovered as sub
E	Electricity (kW)	rec	Recoverable
E'	Electricity bought from the grid (kW)	s	Supplied
Em	Emission	S	Sub-criteria
eng	Engine	sum, win	Summer and winter
er	Earned money (Rial)	T	Temperature ($^{\circ}C$)
ex	Expanse (Rial)	t_{gas}	Buying tariff of natural gas (Rial/ m^3)
EXIR	Exergy increase ratio (%)	t_{bp}, t_{sp}	Buying and selling tariff of power (Rial/kW h)
F	Fuel (kW)	TDC	Tropical and dry in summer, cold in winter (Climate)
FA	Fuzzy algorithm	TDEC	Temperate and dry in summer, extremely cold in winter (Climate)
FCU	Fan coil unit	THC	Temperate and humid in summer, cold in winter (Climate)
FEL, FTL	Following electrical and thermal load	THT	Tropical and humid in summer, temperate in winter (Climate)
FESR	Fuel energy saving ratio (%)	TSHT	Tropical and semi-humid in summer, temperate in winter (Climate)
FLO, PLO	Full and partial load operation	$\dot{W}$	Work rate (kW)
FSS	Following seasonal load	wb	Wet bulb
g	grid	wh	Water heater
GIA	Grey incidence approach	wp, sp, rp	Water, solution and refrigerant pumps
H	Heating load (kW)	y	Yearly
H'	The heating produced by the auxiliary boiler (kW)	η_{CHP}	Combine heat and power efficiency
hg	Hot gas	$\eta_{overall}$	Overall efficiency (%)
i	Investment or emission index (Rial/kW h), (Rial/ m^2), (kg/MW h)	π	Exergy efficiency (%)
I	Total investment (Rial)	ϕ	Exergy rate (kW)
		$\wedge, \vee$	AND, OR logical operators
		0	Thermodynamical dead state as sub

the prime mover must operate in partial load some months, which results in efficiency reduction.

After selection the type of prime mover, sizing of prime mover is the most important parameter. Sizing changes the amount of fuel saving, overall efficiency, environmental pollution, economical parameters and the optimum strategy used to prepare the electrical or thermal loads of building.

Ref. [19] uses two multi-criteria decision-making methods to select the best type of prime mover for five climates in Iran. The authors use 16th sub-criteria from the technological, economical, environmental and social criteria for the comprehensive decision-making. The effect of climate on sizing and designing of CCHP is studied by Ref. [6]. The authors used maximum rectangle method (MRM) to determine the prime mover size of the CCHP system for a similar residential building in five different climates of Iran.

Ref. [20] determines the size and number of micro-gas turbines of a CCHP system for a residential building in Tehran, Ahwaz and Hamedan when using the FTL strategy. This research uses a simple and linear balance equation between the peak loads of the building.

A thermo-economic analysis is presented by Ref. [14] to specify the type and number of required micro-gas turbines to provide the electrical and thermal needs of a commercial building in Tehran urban area during a year. This research maximizes an objective function called annual profit. Refs. [18,21] have used the MRM for sizing the components of the CHP or CCHP systems. The principals of MRM are presented in Refs. [14,18,21]. Ref. [21] considers a constraint on the primary energy saving as the main criteria and using FTL strategy. They used the hourly cooling load for sizing the absorption chiller and the aggregated thermal demand to size the prime mover of a CCHP plant. In 2010, Ref. [18] developed the MRM presented in Ref. [21] to three methods of vertical design, horizontal design and high-level analysis for sizing the prime mover. The only constraint in the vertical and horizontal design is a minimum pre-assumed PES, but in the high-level analysis an economical criteria such as net present value (NPV) is also considered.

In the present paper, a novel method that considers energy, exergy, economical and environmental aspects of the project is

presented for sizing and strategy selection of the prime mover of the CCHP system. By linear combination of the criteria and calculating weight for each criterion a function called multi-criteria sizing function (MCSF) is achieved. This function is used for optimum sizing of the prime mover from the single or multi criteria points of views. The results of sizing are presented for five different climates by considering a similar and hypothetical but very close to real residential buildings in Iran.

2. Formulation

2.1. Calculate the criteria and sub-criteria

In this research, thermodynamical (C_1), economical (C_2) and environmental (C_3) criteria are considered for finding the best prime mover size and strategy for the CCHP system in different climates. Exergy and energy analyses are done for the thermodynamical analyses. The economical evaluation is performed by using NPV, internal rate of return (IRR) and payback period (PB) to find out about the profitability, risk and payback period of investment in CCHP. For the environmental assessment of the CCHP cycle, productions of the NO_x , CO_2 and CO are considered. In the following, the equations used for different evaluations are derived systematically. The magnitudes of the criteria are calculated for both the CCHP cycle and conventional separate production of heating, cooling and power (CSP). The cooling system in both CCHP and CSP is an absorption chiller. An auxiliary boiler and recovered heat from the CCHP cycle are used for providing the heating load of the building and domestic hot water. Fan coil units (FCU) are used to transfer heat and cool to the final users. The schematic of the CCHP and CSP are shown in Fig. 1.

2.1.1. Thermodynamical analyses

Thermodynamical analyses include the energy and exergy analyses. In the energy analysis, the fuel consumption of the CCHP is compared with the CSP. However, in the exergy analysis the overall exergy efficiency of the CCHP is compared with the overall exergy efficiency of the CSP.

In the energy analysis, a fuel vector (F) is defined as below:

$$F^j = (F_P^j, F_C^j, F_H^j, F_D^j) \quad (2)$$

in which the subscripts of P , C , H and D stands for the power, cooling, heating and domestic hot water and superscript $j = 0$ and 1 are for the CSP and CCHP respectively. To calculate the fuel consumption during a year we have 8760 h in one year, hence:

$$\text{Fuel}^j = \sum_{t=1}^{8760} (F_P^j + F_C^j + F_H^j + F_D^j)_t \quad (3)$$

The components of fuel vector for the CSP and CCHP are presented below:

$$\begin{aligned} F_P^0 &= \frac{E_{\text{dem}}}{\eta_{\text{pp}} \eta_g}, F_P^1 = \frac{E + Q_{\text{rec}}}{\eta_{\text{CCHP}}} + \frac{(E'_{\text{dem}})}{\eta_{\text{pp}} \eta_g} \\ F_C^0 &= \frac{C_{\text{dem}}}{\eta_b \text{COP}_{\text{abc}} \epsilon_{\text{FCU}}}, F_C^1 = \frac{C'_{\text{dem}}}{\eta_b \text{COP}_{\text{abc}} \epsilon_{\text{FCU}}} \\ F_H^0 &= \frac{H_{\text{dem}}}{\eta_b \epsilon_{\text{FCU}}}, F_H^1 = \frac{H'_{\text{dem}}}{\eta_b \epsilon_{\text{FCU}}} \\ F_D^0 &= \frac{D_{\text{dem}}}{\epsilon_{\text{wh}}}, F_D^1 = \frac{D_{\text{dem}}}{\epsilon_{\text{wh}}} \end{aligned} \quad (4)$$

In which:

$$\begin{aligned} E &= \begin{cases} E_{\text{nom}} & \text{if } (E_{\text{nom}} \leq E_{\text{dem}}) \vee \text{FLO} \vee [(E_{\text{nom}} \leq E_{\text{dem}}) \wedge \text{PLO}] \\ E_{\text{dem}} & \text{if } [(E_{\text{nom}} > E_{\text{dem}}) \wedge \text{PLO}] \end{cases} \\ Q_{\text{rec}} &= 1.368E + 14.57, 30 \leq E(\text{kW}) \leq 400 \\ Q_{\text{rec}} &= 1.854E, 0 \leq E(\text{kW}) < 30 \\ E'_{\text{dem}} &= \begin{cases} E_{\text{dem}} - E_{\text{nom}} & \text{if } E_{\text{dem}} > E_{\text{nom}} \\ 0 & \text{if } E_{\text{dem}} \leq E_{\text{nom}} \end{cases} \\ C'_{\text{dem}} &= \begin{cases} C_{\text{dem}} - \text{COP}_{\text{abc}} Q_{\text{rec}} & \text{if } C_{\text{dem}} > \text{COP}_{\text{abc}} Q_{\text{rec}} \\ 0 & \text{if } C_{\text{dem}} \leq \text{COP}_{\text{abc}} Q_{\text{rec}} \end{cases} \\ H'_{\text{dem}} &= \begin{cases} H_{\text{dem}} - Q_{\text{rec}} & \text{if } H_{\text{dem}} > Q_{\text{rec}} \\ 0 & \text{if } H_{\text{dem}} \leq Q_{\text{rec}} \end{cases} \end{aligned} \quad (5)$$

Attention must be paid to the water heating system for domestic hot water (DHW) demand. If it is supposed to use the recovered heat for preparing the DHW, therefore $D_{\text{dem}} = 0$ and $H_{\text{dem}} = (\text{heating load} + \text{DHW load})$. However, if a separate water heater is installed $D_{\text{dem}} = \text{DHW load}$ and $H_{\text{dem}} = \text{heating load}$. In addition, the aggregated thermal demand (ATD) of the building is calculated by $\text{ATD} = H_{\text{dem}} + C_{\text{dem}}/\text{COP}_{\text{abc}}$, and correspondingly $\text{ATD}' = H'_{\text{dem}} + C'_{\text{dem}}/\text{COP}_{\text{abc}}$ shows the aggregated thermal lack of the CCHP system that must be compensated by an auxiliary boiler.

In the exergy analysis, the recovered and supplied exergy vectors for the CSP and CCHP are calculated, and used to compute the exergy efficiency during a year as below:

$$\dot{\phi}_s^j = (\dot{\phi}_{s,P}^j, \dot{\phi}_{s,C}^j, \dot{\phi}_{s,H}^j, \dot{\phi}_{s,D}^j) \quad (6)$$

$$\dot{\phi}_r^j = (\dot{\phi}_{r,P}^j, \dot{\phi}_{r,C}^j, \dot{\phi}_{r,H}^j, \dot{\phi}_{r,D}^j) \quad (7)$$

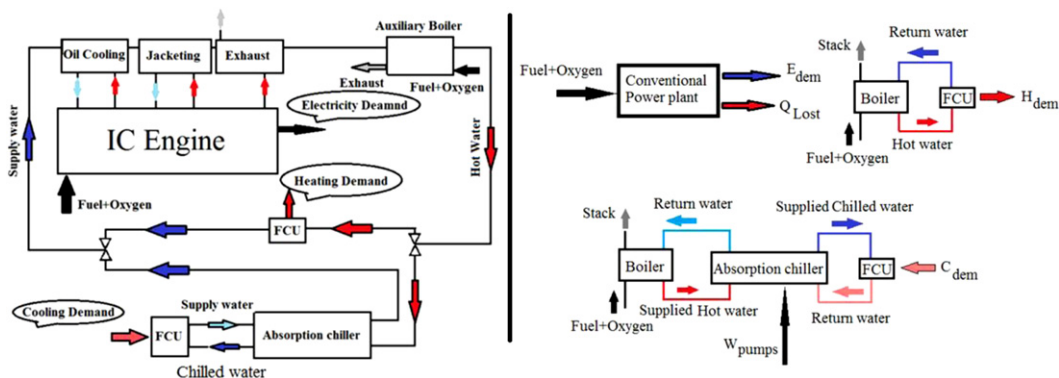


Fig. 1. The CCHP system (left) and CSP system (right).

$$\pi^j = \sum_{t=1}^k \left(\dot{\phi}_r^j \right)_t / \sum_{t=1}^k \left(\dot{\phi}_s^j \right)_t \quad (8)$$

In which k is the number of time steps in one year used for the load calculation, In addition, the components of the exergy vectors are calculated according to the following equations:

$$\begin{aligned} \dot{\phi}_{s,p}^0 &= F_p^0 \left(1 - \frac{T_0}{T_{hg}} \right) - (F_p^0 - E_{dem}) \left(1 - \frac{T_0}{T_{amb}} \right) \\ \dot{\phi}_{s,c}^0 &= \dot{W}_{sp} + \dot{W}_{rp} + \dot{W}_{wp} + F_c^0 \left(1 - \frac{T_0}{T_{hg}} \right) - F_c^0 (1 - \eta_b) \left(1 - \frac{T_0}{T_{amb}} \right) \\ \dot{\phi}_{s,h}^0 &= \dot{W}_{wp} + F_h^0 \left(1 - \frac{T_0}{T_{hg}} \right) - F_h^0 (1 - \eta_b) \left(1 - \frac{T_0}{T_{amb}} \right) \\ \dot{\phi}_{s,d}^0 &= F_d^0 \left(1 - \frac{T_0}{T_{hg}} \right) - F_d^0 (1 - \eta_b) \left(1 - \frac{T_0}{T_{amb}} \right) \end{aligned} \quad (9A)$$

$$\begin{aligned} \dot{\phi}_{r,p}^0 &= E_{dem} \\ \dot{\phi}_{r,c}^0 &= C_{dem} \left(1 - \frac{T_0}{T_{room}} \right) \\ \dot{\phi}_{r,h}^0 &= H_{dem} \left(1 - \frac{T_0}{T_{room}} \right) \\ \dot{\phi}_{r,d}^0 &= D_{dem} \left(1 - \frac{T_0}{T_{room}} \right) \end{aligned} \quad (9B)$$

$$\begin{aligned} \dot{\phi}_{s,p}^1 &= F_p^1 \left(1 - \frac{T_0}{T_{hg}} \right) - (F_p^1 - E - Q_{rec}) \left(1 - \frac{T_0}{T_{amb}} \right) + E'_{dem} \\ \dot{\phi}_{s,c}^1 &= \dot{W}_{sp} + \dot{W}_{rp} + \dot{W}_{wp} + F_c^1 \left(1 - \frac{T_0}{T_{hg}} \right) - F_c^1 (1 - \eta_b) \left(1 - \frac{T_0}{T_{amb}} \right) \\ \dot{\phi}_{s,h}^1 &= \dot{W}_{wp} + F_h^1 \left(1 - \frac{T_0}{T_{hg}} \right) - F_h^1 (1 - \eta_b) \left(1 - \frac{T_0}{T_{amb}} \right) \\ \dot{\phi}_{s,d}^1 &= F_d^1 \left(1 - \frac{T_0}{T_{hg}} \right) - F_d^1 (1 - \eta_b) \left(1 - \frac{T_0}{T_{amb}} \right) \end{aligned} \quad (10A)$$

$$\begin{aligned} \dot{\phi}_{r,p}^1 &= E + E'_{dem} + \dot{\phi}_{Q_{rec}} \\ \dot{\phi}_{r,c}^1 &= C'_{dem} \left(1 - \frac{T_0}{T_{room}} \right) \\ \dot{\phi}_{r,h}^1 &= H'_{dem} \left(1 - \frac{T_0}{T_{room}} \right) \\ \dot{\phi}_{r,d}^1 &= D_{dem} \left(1 - \frac{T_0}{T_{room}} \right) \end{aligned} \quad (10B)$$

In which, the recovered heat sources include the exhaust gases, water-jacketing and oil cooling system, it is assumed that they approximately account for 50%, 35% and 15% of the total recovered heat from the engine respectively. In addition, T_{amb} is defined for each city according to the weather data [19,24].

$$\begin{aligned} Q_{rec} &= Q_{oil} + Q_{jacketing} + Q_{exhaust} \\ \dot{\phi}_{Q_{rec}} &= Q_{oil} \left(1 - \frac{T_0}{T_{oil}} \right) + Q_{jacketing} \left(1 - \frac{T_0}{T_{jacketing}} \right) \\ &\quad + Q_{exhaust} \left(1 - \frac{T_0}{T_{exhaust}} \right) \end{aligned} \quad (11A)$$

$$T_{amb} = \begin{cases} T_{db,sum} & \text{if } (H_{dem} = 0 \wedge C_{dem} \neq 0) \\ T_{db,win} & \text{if } (C_{dem} = 0 \wedge H_{dem} \neq 0) \\ T_{room} & \text{if } H_{dem} = C_{dem} = 0 \end{cases} \quad (11B)$$

$$T_{room} = \begin{cases} T_{room,sum} & \text{if } (C_{dem} = 0 \wedge H_{dem} \neq 0) \\ T_{room,win} & \text{if } (H_{dem} = 0 \wedge C_{dem} \neq 0) \\ (T_{room,sum} + T_{room,win})/2 & \text{if } H_{dem} = C_{dem} = 0 \end{cases} \quad (11C)$$

The input data for the thermodynamical analyses are given as follow; $\eta_{pp} = 0.3$, $\eta_g = 0.85$, $\eta_b = 0.8$, $\varepsilon_{FCU} = 0.85$, $\varepsilon_{wh} = 0.85$, $\eta_{CHP} = 0.8$, $COP_{abc} = 0.7$, $\dot{W}_{sp} + \dot{W}_{rp} = 0.007 C_{nom} (\text{kW})$, $\dot{W}_{water\ pump} = 0.005 \max(C_{dem}, H_{dem}) (\text{kW})$, $T_0 = 15^\circ\text{C}$, $T_{hg} = 1000^\circ\text{C}$, $T_{oil} = 60^\circ\text{C}$, $T_{jacketing} = 100^\circ\text{C}$, $T_{exhaust} = 540^\circ\text{C}$, $T_{room,sum} = 25^\circ\text{C}$, $T_{room,win} = 22^\circ\text{C}$, $T_{db,sum, Tehran} = 38^\circ\text{C}$, $T_{db,win, Tehran} = -2.9^\circ\text{C}$, $T_{db,sum, Ahwaz} = 46.74^\circ\text{C}$, $T_{db,win, Ahwaz} = 8.73^\circ\text{C}$, $T_{db,sum, Bandar Anzali} = 29.76^\circ\text{C}$, $T_{db,win, Bandar Anzali} = 4.61^\circ\text{C}$, $T_{db,sum, Chabahar} = 33.55^\circ\text{C}$, $T_{db,win, Chabahar} = 16.87^\circ\text{C}$, $T_{db,sum, Kmayaran} = 36.82^\circ\text{C}$, $T_{db,win, Kmayaran} = -4.88^\circ\text{C}$.

2.1.2. Economical analyses

In the economical analyses, the NPV, IRR and PB of the CCHP system are calculated. The initial investment is a key parameter in the computation of the NPV and IRR. The following equation is recommended for calculation of the initial investment cost (I) for the CSP and CCHP systems:

$$I = ii_p^j + ii_c^j + ii_h^j + ii_d^j \quad (12)$$

In which the ii is the initial investment cost for each part of the CSP or CCHP systems.

$$ii_p^0 = \text{Subscription fee to grid}, ii_p^1 = E_{nom} \cdot i_p^1 \quad (13)$$

$$\begin{aligned} ii_c^0 &= C_{nom} \cdot i_c^0, ii_c^1 = C_{nom} \cdot i_c^1 \\ C_{nom} &= \max(C_{dem}) \end{aligned} \quad (14)$$

$$\begin{aligned} ii_h^0 &= H_{nom} \cdot i_h^0, ii_h^1 = (H_{nom} - Q_{rec}) \cdot i_h^1 \\ H_{nom} &= \max(H_{dem}, C_{dem}/COP_{abc}) \end{aligned} \quad (15)$$

$$\begin{aligned} ii_d^0 &= D_{nom} \cdot i_d^0, ii_d^1 = D_{nom} \cdot i_d^1 \\ D_{nom} &= \max(D_{dem}) \end{aligned} \quad (16)$$

In which i is the index price (Rials/kW) for each part of system. To calculate the annual cash flow (cf) for the CSP and CCHP systems, the annual expanse vector (exv) is subtracted from the annual earning vector (erv) as below:

$$erv^j = (er_p^j, er_c^j, er_h^j, er_d^j) \quad (17)$$

$$exv^j = (ex_p^j, ex_c^j, ex_h^j, ex_d^j) \quad (18)$$

$$cf_y^j = \sum_{t=1}^{8760} (erv^j - exv^j)_t \quad (19)$$

$$NPV^j = \sum_{y=1}^n \frac{cf_y^j}{(1+r)^y} - I^j \quad (20)$$

$$\sum_{y=1}^n \frac{cf_y^j}{(1+IRR)^y} \bigg|_{IRR} = I^j \quad (21)$$

In which, $n = 30$ is the lifetime of the project. Also, the erv^j and exv^j are calculated as below:

$$\begin{aligned} er_p^0 &= 0, ex_p^0 = E_{dem} \cdot t_{bp} \\ er_c^0 &= 0, ex_c^0 = F_c^0 \cdot t_{gas} \\ er_h^0 &= 0, ex_h^0 = F_h^0 \cdot t_{gas} \\ er_d^0 &= 0, ex_d^0 = F_d^0 \cdot t_{gas} \end{aligned} \quad (22)$$

$$\begin{aligned} er_p^1 &= E_{dem} \cdot t_{bp} + (E - E_{dem}) \cdot t_{sp}, ex_p^1 = F_p^1 \cdot t_{gas} \\ er_c^1 &= \frac{Q_{rec}}{\eta_b} \cdot t_{gas}, ex_c^1 = F_c^1 \cdot t_{gas} \\ er_h^1 &= \frac{Q_{rec}}{\eta_b} \cdot t_{gas}, ex_h^1 = F_h^1 \cdot t_{gas} \\ er_d^1 &= 0, ex_d^1 = F_d^1 \cdot t_{gas} \end{aligned} \quad (23)$$

The third criterion that is usually used in the economical analyses is the payback period of the project. This criterion calculates the years that it takes to recover the original initial investment cost, and is calculated as below:

$$PB^j = j / cf_y^j = \begin{cases} PB^j & \text{if } cf_y > 0 \\ \text{not applied} & \text{if } cf_y \leq 0 \end{cases} \quad (24)$$

The input data for the economical analyses are given as follow; $t_{bp} = 485$ Rials/kW h, $t_{sp} = 392$ Rials/kW h, $t_{gas} = (1 - off_{CCHP}) \times 700$ Rials/m³, $off_{CCHP} = 20\%$, $ii_p^0 = 3.45 \times 10^6$ Rials, in which off_{CCHP} is the government discount for selling natural gas to the CCHP users. In addition, the equations for calculating the components' price are presented in Table 4 [25].

2.1.3. Environmental analyses

In the environmental analyses, an environmental vector is defined for the CO₂, CO and NO_x production in the CSP and CCHP systems as follow:

$$X^j = (X_p^j, X_c^j, X_h^j, X_d^j) \quad (25)$$

In which X can be CO₂, CO or NO_x. In addition, the components of the environmental vector are as below:

$$\begin{aligned} X_p^0 &= E_{dem} \cdot i_{X,p}^0, X_p^1 = E \cdot i_{X,p}^1 + E'_{dem} \cdot i_{X,p}^0 \\ X_c^0 &= C_{dem} \cdot i_{X,c}^0, X_c^1 = C'_{dem} \cdot i_{X,c}^1 \\ X_h^0 &= H_{dem} \cdot i_{X,h}^0, X_h^1 = H'_{dem} \cdot i_{X,h}^1 \\ X_d^0 &= D_{dem} \cdot i_{X,d}^0, X_d^1 = D_{dem} \cdot i_{X,d}^1 \end{aligned} \quad (26)$$

Therefore, the environmental emission production for each pollutant (Em) during a year for CSP and CCHP systems can be calculated according to the following equation:

$$Em_X^j = \sum_{t=1}^{8760} (X_p^j + X_c^j + X_h^j + X_d^j)_t \quad (27)$$

The input data for the environmental analyses are given as follow [26,27]: $i_{CO,p}^0 = 4$, $i_{CO,c}^0 = 0.1274$, $i_{CO,h}^0 = 0.1274$, $i_{CO,d}^0 = 0.1274$, $i_{CO_2,p}^0 = 700$, $i_{CO_2,c}^0 = 182.04/COP_{abc}$, $i_{CO_2,h}^0 = 182.04$, $i_{CO_2,d}^0 = 182.04$, $i_{NO_x,p}^0 = 300$, $i_{NO_x,c}^0 = 0.1532$, $i_{NO_x,h}^0 = 0.1532$, $i_{NO_x,d}^0 = 0.1532$, $i_{CO,p}^1 = 0.8$, $i_{CO,c}^1 = 0.1274$, $i_{CO,h}^1 = 0.1274$, $i_{CO,d}^1 = 0.1274$, $i_{CO_2,p}^1 = 430$, $i_{CO_2,c}^1 = 182.04/COP_{abc}$, $i_{CO_2,h}^1 = 182.04$, $i_{CO_2,d}^1 = 182.04$, $i_{NO_x,p}^1 = 0.7$, $i_{NO_x,c}^1 = 0.1532$, $i_{NO_x,h}^1 = 0.1532$, $i_{NO_x,d}^1 = 0.1532$, the units of the above parameters is kg/MW h.

2.2. Normalization of the criteria

In order to normalize the sub-criteria of S , if it is a cost or “the lower the better” like the fuel consumption, then the reduction ratio of S can be calculated as below:

$$S_{ij}^N = 100(S^0 - S^1)/S^0 \quad (28)$$

However, if S is a benefit or “the higher the better”, then the increase ratio of S can be calculated as below:

$$S_{ij}^N = 100(S^1 - S^0)/S^1 \quad (29)$$

Eqs. (28) and (29) are used to normalize the technological and environmental sub-criteria. In order to normalize the economical sub-criteria of NPV, IRR and PB the following techniques are used:

The NPV of separate production is always negative, because this system never has positive cash flow for the owner; also only the CCHP projects with positive NPV is economically acceptable. Hence, the NPV increase ratio is calculated as below:

$$NPV^N = 100 \frac{NPV^1}{NPV^1 - NPV^0} = \begin{cases} NPV^N & \text{if } NPV^1 > 0 \\ 0 & \text{if } NPV^1 \leq 0 \end{cases} \quad (30)$$

For an economical project, the IRR shows the risk of investment, and must be greater than the interest rate (r). Due to the negative NPV^0 , the IRR^0 is always smaller than the r , for this reason the IRR increase ratio is calculated as below:

$$IRR^N = 100 \frac{IRR^1 - r}{IRR^1} = \begin{cases} IRR^N & \text{if } IRR^1 > r \\ 0 & \text{if } IRR^1 \leq r \end{cases} \quad (31)$$

The third economical criterion, PB, cannot be defined for the separate production system because there is no positive cash flow for the separate production. Therefore, it is normalized as below to be used in the MCSF:

$$PB^N = \frac{100}{PB^1} = \begin{cases} PB^N & \text{if } PB^1 > 1 \\ 1 & \text{if } PB^1 \leq 1 \end{cases} \quad (32)$$

2.3. Conditions and constraints to find E_{nom}^{ij}

In order to generate the MCSF, we need to calculate the engine size (E_{nom}) recommended by each criterion. For this purpose, the following procedure is used to calculate corresponding E_{nom} for each criterion. For the thermodynamical and environmental sub-criteria:

$$E_{nom}^{ij} = \{E_{nom} | S_{ij}^N \text{ is max, } i = 1, 3, E_{min} \leq E_{nom} \leq E_{max}\} \quad (33A)$$

In addition, for the economical sub-criteria, the engine size is chosen for the conditions in which the project becomes profitable, safe, and the original investment recovers less than 6 years. Hence:

$$E_{nom}^{ij} = \{E_{nom} | S_{ij}^N > 0, i = 2, j = 1, 2, E_{min} \leq E_{nom} \leq E_{max}\} \quad (33B)$$

$$E_{nom}^{ij} = \{E_{nom} | S_{ij}^N > \frac{100}{6}, i = 2, j = 3, E_{min} \leq E_{nom} \leq E_{max}\} \quad (33C)$$

If a criterion (S_{mn}^N) continuously increases, as the E_{nom} increases, then the upper bound, $E_{max} = \max\{E_{nom}^{ij}, i \neq m, j \neq n\}$. It means that E_{max} will be limited to the biggest size recommended by

other criteria. This constraint helps to avoid over sizing of engine. In addition, the lower bound is limited by the economical criteria to make the project economical. Then, $E_{\min} \leq \min\{E_{\text{nom}}^{ij}, i = 3, j = 1, 2, 3\}$.

2.4. Calculate the normalized weight matrix

The degree of importance of each criterion (or sub-criterion) with respect to the other criteria (or sub-criteria) is considered by calculating the weight of each criterion (or sub-criterion). For this purpose, the pairwise comparison matrix (PC) between the n criteria is made as below:

$$PC = [PC_{ij}]_{n \times n} \quad (34)$$

In which PC_{ij} represents the importance of i th criterion with respect to j th criterion. In the fuzzy algorithm, a linguistic pairwise comparison presented by Ref. [22] is used to provide the PC matrix (Table 1). However, in the Grey incidence approach (GIA) an equation is recommended as below:

$$PC_{ij} = 1 \pm 0.1\delta, \delta = 0, 1, 2, \dots, 10 \quad (35)$$

In which the plus sign is for the time when the i th criterion is δ degree more important than the j th criterion, but the minus sign is for the time when the j th criterion is δ degree more important than the i th criterion. In this study, to simplify the pairwise comparisons a combination of the methods used in the FA and GIA is used. Table 1 shows the combined method for pairwise comparison [19]. The pairwise comparisons of the main criteria and sub-criteria are presented in Table 2. In this table, $S_{11}^N, S_{12}^N, S_{21}^N, S_{22}^N, S_{23}^N, S_{31}^N, S_{32}^N$ and S_{33}^N are symbols for fuel energy saving ratio (FESR), exergy increase ratio (EXIR), NPV increase ratio, IRR increase ratio, PB inverse, NO_x reduction ratio, CO_2 reduction ratio, and CO reduction ratio respectively. The subjective weighting method of analytic hierarchy process (AHP) is used that is shortly presented below [4]:

$$\begin{aligned} \rho_j &= \sum_{i=1}^n PC_{ij} \\ \rho_{\max} &= \max(\rho_1, \rho_2, \dots, \rho_n) \\ \rho_{\min} &= \min(\rho_1, \rho_2, \dots, \rho_n) \\ \theta &= \rho_{\max} / \rho_{\min} \end{aligned} \quad (36)$$

$$b_{ik} = \begin{cases} 1 + (\rho_i - \rho_k) / \rho_{\min}, & \rho_i \geq \rho_k, \theta \neq 1 \\ (1 + (\rho_i - \rho_k) / \rho_{\min})^{-1}, & \rho_i < \rho_k, \theta \neq 1 \\ 0 & \theta = 1 \end{cases} \quad (37)$$

$$c_{ik} = \log b_{ik}, \quad i, k = 1, 2, \dots, n \quad (38)$$

$$d_{ik} = \frac{1}{n} \sum_{l=1}^n (c_{il} - c_{kl}) \quad (39)$$

Table 1
Combine pairwise comparison of fuzzy and GIA methods.

Fuzzy linguistic comparison of the i th criteria with respect to the j th criteria	GIA	
	PC	PC(R)
Just equal (JE)	1	1
Equally important (EI)	1.2	0.8
Weakly more important (WMI)	1.4	0.6
Strongly more important (SMI)	1.6	0.4
Very Strongly more important (VSMI)	1.8	0.2
Absolutely more important (AMI)	1.9	0.1

Table 2
Pairwise comparison for the main criteria and sub-criteria.

	C_1	C_2	C_3		S_{11}^N	S_{12}^N	
C_1	JE	EI	SMI(R)	S_{11}^N	JE	EI(R)	
C_2	EI(R)	JE	SMI(R)	S_{12}^N	EI	JE	
C_3	SMI	SMI	JE				
	S_{21}^N	S_{22}^N	S_{23}^N		S_{31}^N	S_{32}^N	S_{33}^N
S_{21}^N	JE	SMI(R)	VSMI(R)	S_{31}^N	JE	EI	EI
S_{22}^N	SMI	JE	SMI(R)	S_{32}^N	EI(R)	JE	EI
S_{23}^N	VSMI	SMI	JE	S_{33}^N	EI(R)	EI(R)	JE

$$b'_{ik} = 10^{d_{ik}} \quad (40)$$

Therefore, the eigenvector of the AHP is given as below:

$$E_i = \sqrt[n]{\prod_{k=1}^n b'_{ik}}, \quad i = 1, 2, \dots, n \quad (41)$$

Finally, the normalized weight matrix would be as follow:

$$\omega_i = \frac{E_i}{\sum_{i=1}^n E_i} \quad (42)$$

2.5. Calculate the MCSF

In the present study, a MCSF is defined to optimize the size of the prime mover and the strategy used in the CCHP cycle. The MCSF uses technological (C_1), economical (C_2) and environmental (C_3) criteria. Each criterion consists of some sub-criteria. The MCSF is stated as below:

$$MCSF = \sum_{i=1}^m \beta_i \omega_i C_i, \quad \sum_{i=1}^m \omega_i = 1 \quad (43)$$

In which the ω_i and m are the weight of each criterion and number of main criteria respectively, and $\beta \in \{0, 1\}$ is the criterion coefficient and is used for the purpose of single or multi criteria evaluations. When a criterion is supposed to be counted in the evaluations $\beta = 1$, otherwise $\beta = 0$. The C_i is also stated based on the corresponding E_{nom}^{ij} of sub-criteria of each main criterion as below:

$$C_i = \sum_{j=1}^n \omega_{ij} \cdot E_{\text{nom}}^{ij} \quad (44)$$

In which, n is the number of sub-criteria defined for each main criterion and, ω_{ij} is the weight of each sub-criterion. The optimum size of the engine is equal to the magnitude of MCSF. Hence,

$$E_{\text{nom}}^{\text{optimum}} = MCSF \quad (45)$$

2.6. Strategy classification

As discussed, the literature introduces three strategies of FEL, FTL and FSS. In all of the researches concerning about the strategy, they assume one of the strategies from the beginning and calculate the corresponding engine size, or they consider three types of strategies and according to the energy, economical and or environmental evaluations they finally choose one of the strategies as the best one [12–18,20,21]. In fact, they specify the size of engine according to the strategy assumed and the electrical and thermal loads of the building. It means that only three engine sizes are calculated for the three strategies and the best size and strategy is chosen among the three sizes. However, is there any guarantee that

the best size is confidently one of the three sizes? According to this research, the answer is, no.

The authors of the present research believe that strategy is not an independent variable and should not be treated like that; because it can lead to non-optimized solutions. Strategy is completely dependent on the size of the prime mover, and the operation type (partial or full load) of the engine. The MCSF helps us to size the prime mover and decide about the operation type. Therefore, the strategy is not limited to the three types. As a guideline, Table 3 presents a classification for five strategy types for the time when the engine is operating at full load.

3. Case study

The residential building and the climates, which are considered in this study, are the same as that of Refs. [6,19]. The building is hypothetical, has four floors, eight units, and total living area of 1200 m² for 32 inhabitants. The building is considered for five nominated cities of Ahwaz, Tehran, Bandar Anzali, Chabahar and Kamyaran located in the climates of TSHT, TDC, THC, THT and TDEC respectively. To calculate the electrical load of building, the power consumptions of the refrigerant pump and solution pump of the absorption chiller and the water recirculation pump that were not considered in the Ref. [19] are considered in this research. For this reason, the electrical load reported in this study is a little bit different with respect to that presented in Ref. [19].

4. Results

4.1. Load results

In addition, according to the findings of [6] it is considered that the prime mover is always operating at full load. Fig. 2 presents the maximum ATD, maximum E_{dem} and power to heat ratio of the building (PHR_{dem}), as it can be seen due to the small changes in the electrical load; the PHR_{dem} of building has changed slightly (with respect to Fig. 10 of Ref. [19]). The power to heat ratio of the building (PHR_{dem}) varies from 0.16 to 0.34 for the nominated cities from the five climates; it means that the heat demand is 2.94–6.25 times the power demand of the building. The power to heat ratio of the internal combustion engine (PHR_{eng}) that is considered as the prime mover for the CCHP system varies from 0.5 to 0.74 [23], which means that the Q_{rec} is only 1.35–2 times the E_{nom} . This comparison tells us if we follow the electrical load to provide the heat demand a huge auxiliary boiler is necessary, this may decrease the overall efficiency and exergy efficiency, and increase the environmental pollution, but if we follow the thermal load an enormous prime mover should be used that increases the initial investment cost of the CCHP. According to this discussion, the optimum size and strategy should be chosen based on the energy, exergy, economical and environmental analyses as follow.

Table 3
Strategy classification for a prime mover at full load operation.

Strategies	Conditions	E_{sell}	E_{purchase}
Lower FEL (LFEL)	$E_{\text{nom}} < E_{\text{dem,max}}$	0	$\sum(E_{\text{dem}} - E_{\text{nom}})$
FEL	$E_{\text{nom}} = E_{\text{dem,max}}$	$\sum(E_{\text{nom}} - E_{\text{dem}})$	0
Following electrical, partial thermal load (FEPTL)	$E_{\text{FEL}} < E_{\text{dem,max}} < E_{\text{FTL}}$	$\sum(E_{\text{nom}} - E_{\text{dem}})$	0
FTL	$Q_{\text{rec}} = Q_{\text{dem,max}}$ $E_{\text{nom}} = E_{\text{FTL}} = f(Q_{\text{rec}})$	$\sum(E_{\text{nom}} - E_{\text{dem}})$	0
Upper FTL (UFTL)	$E_{\text{nom}} > E_{\text{FTL}}$	$\sum(E_{\text{nom}} - E_{\text{dem}})$	0

4.2. Weighting results

The weight of each criterion with respect to other criteria is calculated by using the AHP method and is reported in Table 5. According to this table the economical criteria receives the biggest weight (0.434), then thermodynamical criteria (0.366) and finally the environmental criteria (0.200). Among the thermodynamical criteria, the energy weight (0.550) is slightly greater than exergy (0.450). Among the economical criteria the NPV weight (0.522) is the biggest, because this criterion talks about the profitability of the project while considering the interest rate (in this study $r = 15\%$). The IRR weight (0.303) receives the second priority, the higher the IRR (with respect to the r), the smaller the risk of investment. About the environmental sub-criteria, CO weight (0.380) is of greatest importance, because producing this toxic gas in the residential applications is very dangerous. After CO, the CO₂ weight (0.331) is placed in the second order, because of its great impact on the global warming. The NO_x weight is 0.289 and is placed at the third stage.

4.3. Single criterion sizing results

The single criteria sizing refers to finding the E_{nom}^{ij} for each criterion according to the conditions and constraints defined in the previous sections. The results of single criteria sizing are presented in Figs. 3–10 and Table 6. Fig. 3 presents the impact of changing the engine size on the FESR; it shows that there is a maximum of FESR for each climate. It shows that FESR starts increasing rapidly by increasing the E_{nom} until it reaches a maximum point and then decreases slowly. The reason is that as the E_{nom} increases the Q_{rec} increases as well, this increases the FESR until the Q_{rec} reaches the ATD. When the Q_{rec} becomes greater than the ATD, the heat is wasted and the FESR decreases accordingly. This may happen during days and nights, but the yearly data are presented in the results. The E_{nom} that maximizes the yearly FESR is presented for each climate in Table 6. Fig. 4 shows the EXIR versus E_{nom} , as it can be seen the EXIR increases as the E_{nom} increases. It is clear that it is impossible to find an E_{nom} to maximize the EXIR. To solve this problem in the MCSF, the biggest E_{nom} recommended for other criteria is chosen for the criterion. For example, according to Table 6, the NO_x reduction ratio for all of the climates recommends the biggest E_{nom} among the other criteria; therefore, the E_{nom} for the EXIR is the same as E_{nom} for the NO_x reduction ratio. This also avoids unnecessary over sizing of engine.

Figs. 5–7 present the normalized economical sub-criteria versus the E_{nom} . The constraints for the economical evaluations are presented in Table 6 as well. Positive NPV means that the project is profitable, IRR shows the risk of investment, and must be greater than the interest rate (r) as a minimum expectation. In addition, the maximum PB defined for this study is assumed 6 years. These constraints provide the minimum economical expectation of the designer. It is clear that these constraints can be considered more conservatively. For example it can be considered that $\text{NPV} > 0.5I_0$, $\text{IRR} > (r + 5\%)$ and $\text{PB} < 5\text{years}$. Figs. 5 and 6 present the NPV^N and IRR^N . Negative NPV^N and IRR^N are set equal to zero and only the positive values are economical. These two criteria recommend minimum engine sizes of 63, 165, 66, 148 and 59 (kW) for the cities of Tehran, Ahwaz, Bandar Anzali, Chabahar, and Kamyaran respectively. These sizes guarantee the profitability and safety of investment in CCHP. The third economical criterion concerns about the period it takes to recover the initial investment (I_0) which is different for each climate. The PB^N is shown in Fig. 7 and the 100/6 line is drawn to illustrate the limit for the sizes that result in PB of less than 6 years. The E_{nom} s with PB^N of greater than 100/6 mean payback period less than 6 years. The E_{nom} s recommended by PB

Table 4
Cost curves of components.

Component	Equation	Description
Steel boiler	$y = 1.524 \times 10^{13} x^{-3.212} + 1.033 \times 10^6 R_{\text{square}} = 0.9951$	x (kW), y (Rials/kW), $x < 3486$, Fire tube boiler, pressure 4 bar, maximum temperature of 120 °C, for every 1 bar pressure increase, the cost increases 5%. http://www.spac.ir .
Gas internal combustion engine	$y = 1.1 \times (1.881 \times 10^{21} x^{-10.33} + 1.062 \times 10^7) + y_{\text{OM}}$ $y_{\text{OM}} = 0.40458 + (324,890/x) R_{\text{square}} = 0.9562$	x (kW), y (Rials/kW), $x < 500$, Costs are expressed in Rials per kilowatt of installed capacity. Data from California energy commission, 2004, CERTS Program Office Lawrence Berkeley National Laboratory, 1USD = 12,260 Rials, the 1.1 is the coefficient to consider the heat exchanger costs.
Absorption chiller	$y = 12,260(-35.4 \log(x) + 431)$	x (kW), y (Rials/kW), Data from California energy commission, 2004, CERTS Program Office Lawrence Berkeley National Laboratory, 1USD = 12,260 Rials

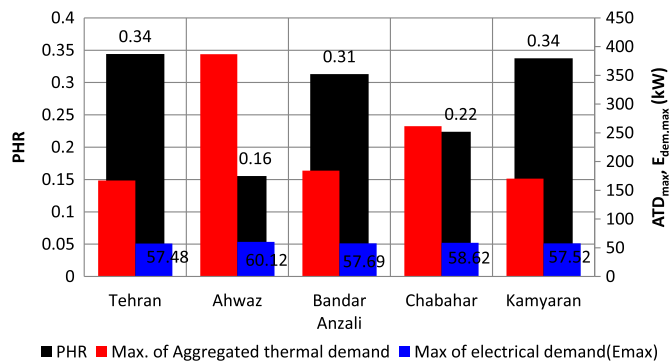


Fig. 2. PHR, maximum of ATD and electrical demand of building.

are 82, 217, 86, 206 and 77 (kW) for the cities of Tehran, Ahwaz, Bandar Anzali, Chabahar, and Kamyaran respectively.

Figs. 8–10 represent the pollution reduction ratio of CO₂, CO and NO_x respectively. The CO₂ reduction ratio recommends E_{nom} s of 58, 115, 58, 93 and 57 (kW). The behavior of pollution reduction ratio is the same as FESR, because the pollutant production is directly proportional to the fuel consumption. As it can be seen the CO and NO_x reduction ratio changes very little after a certain size of E_{nom} , but however a maximum point can be found for these criteria. The E_{nom} recommended by the CO and NO_x reduction ratio are shown in Table 6. As it can be seen, the E_{nom} s recommended by different criteria is different and it is very difficult to use one of them as a reference to find the optimum size for the engine. Therefore, a solution should be proposed to recommend an engine size to use all of the criteria and their corresponding engine sizes. The MCSF is the proposal and the results are presented in the following.

4.4. Multi-criteria sizing results

As discussed in the previous section, it is very difficult to use a single criterion to size the prime mover, because different criteria

Table 5
Weights of criteria according to the AHP.

Main criteria		Sub-criteria	
Technological	0.366	Energy	0.550
		Exergy	0.450
Economical	0.434	NPV	0.522
		IRR	0.303
		PB	0.175
Environmental	0.200	NO _x	0.289
		CO ₂	0.331
		CO	0.380

give different E_{nom} s. To solve the diversity of E_{nom} s from different criteria and simultaneously make use of the advantages of all criteria a MCSF is proposed. The MCSF is calculated according to the weights of criteria, weights of sub-criteria, and E_{nom} s by using Eqs. (43)–(45). The results of multi criteria sizing are presented in Table 7. This table reports very important results including, $E_{\text{nom}}^{\text{optimum}}$, FESR, EXIR, NPV, IRR, PB, CO reduction ratio, CO₂ reduction ratio, NO_x reduction ratio, I_0 , PVP (present value percentage) and the auxiliary boiler capacity for the CCHP system in the five climates. The $E_{\text{nom}}^{\text{optimum}}$ for different cities of Tehran, Ahwaz, Bandar Anzali, Chabahar and Kamyaran are 83, 211, 88, 161, and 78 (kW). These engine sizes give annual saving energy of 36.23, 35.27, 34.69, 40.08 and 37.38% for the 5 cities mentioned above respectively. The EXIR for the five climates ranges from 90% to 95%. About this parameter, as the engine size increases the EXIR increases as well. When studying Table 7, it can be seen that due to considering non-conservative economical constraints, the NPV after 30 years is not

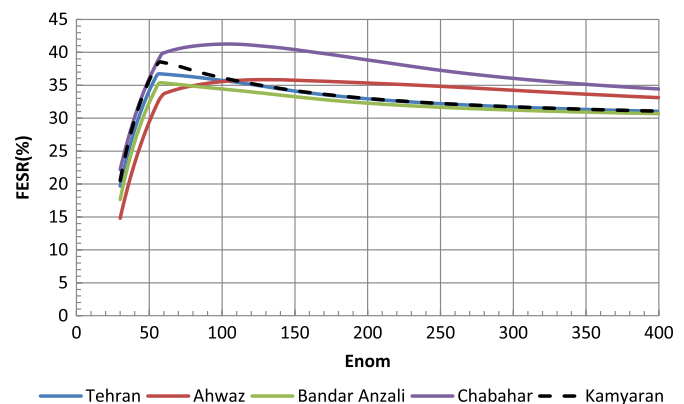


Fig. 3. Impact of engine size (E_{nom}) on the annual S_{11}^N for 5 climates.

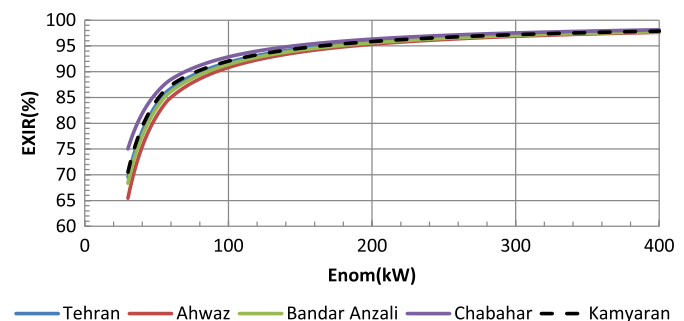


Fig. 4. Impact of engine size (E_{nom}) on the annual S_{12}^N for 5 climates.

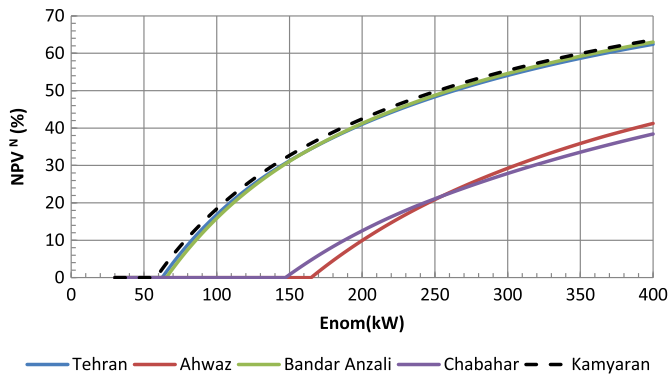


Fig. 5. Impact of engine size (E_{nom}) on the annual NPV^N for 5 climates.

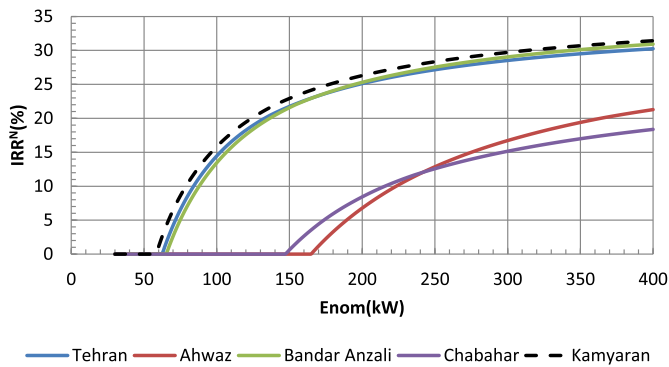


Fig. 6. Impact of engine size (E_{nom}) on the annual IRR^N for 5 climates.

considerable (from 7.12MT for Chabahar to 30.04MT for Ahwaz); the risk margin (IRR-r) is very narrow (from 0.44% for Chabahar to 1.67% for Bandar Anzali) and the PB is about 6 years. The economical constraints depend on the designer decision, they can be considered more conservative as discussed previously, and as a result, the economical criteria will improve accordingly. The environmental analyses show very considerable reduction in the pollutants. Green house gas, CO₂ reduces annually from 43.51% for Ahwaz to 46.98% for Chabahar. CO and NO_x reduction of about 80 and 90% are achieved for all of the climates.

The initial investment, I_0 of the CCHP for the 5 climates is very different. It varies from 137.27MT for Kamyaran to 346.97MT for Ahwaz. By presenting an evaluation between NPV with the corresponding I_0 , the present value percentage (PVP) is calculated. According to the PVP that is presented in Table 7, using the CCHP in

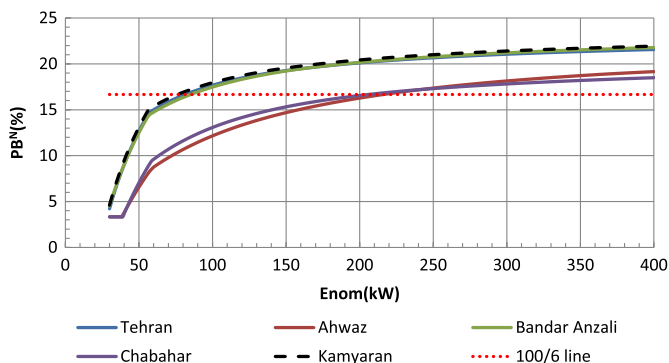


Fig. 7. Impact of engine size (E_{nom}) on the annual PVP^N for 5 climates.

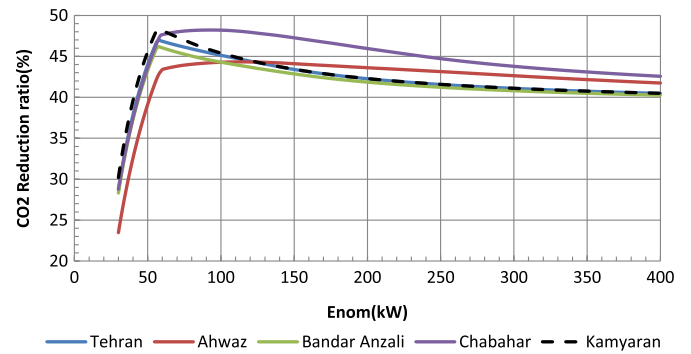


Fig. 8. Impact of engine size (E_{nom}) on the annual S_{31}^N for 5 climates.

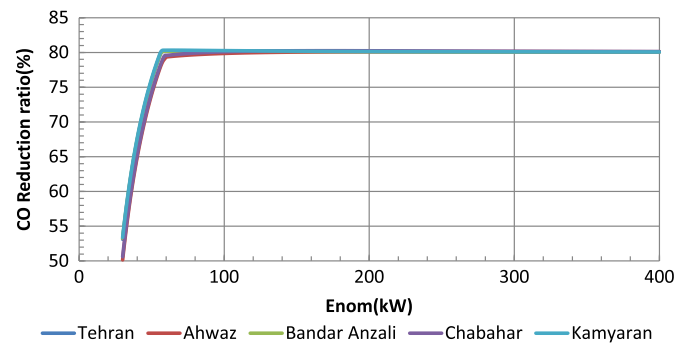


Fig. 9. Impact of engine size (E_{nom}) on the annual S_{32}^N for 5 climates.

Bandar Anzali is the most economical, but in Chabahar it is the least economical. The CCHP in Tehran and Kamyaran is also more economical with respect to Ahwaz.

The auxiliary boiler capacity for Ahwaz is very big; this is due to very high cooling load of Ahwaz. This big size of boiler avoids over sizing the engine. Figs. 11 and 12 present the effect of E_{nom} on the auxiliary boiler capacity and I_0 for the 5 climates. Fig. 11 also shows the engine size that result in not using an auxiliary boiler in the system.

As an overall discussion on the results of this section, the initial investment cost for two cities of Chabahar and Ahwaz is too large with respect to other cities. This high initial investment probably has negative impact on the users' decision to install CCHP systems. By considering two techniques this problem may be solved. Firstly, thermal storage system beside the solar heating systems or electrical storage system beside the photovoltaic cells can be integrated with the proposed CCHP system. This integration can result in

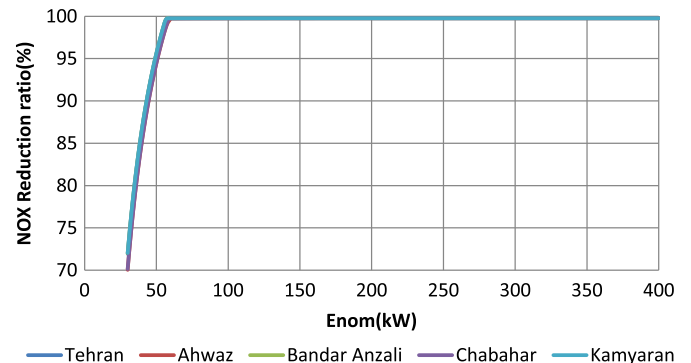


Fig. 10. Impact of engine size (E_{nom}) on the annual S_{33}^N for 5 climates.

Table 6
The corresponding E_{nom}^{ij} for each sub-criterion in the 5 climates

Conditions	E_{nom}^{ij} (kW)				
	Tehran	Ahwaz	Bandar Anzali	Chabahar	Kamyaran
Maximizing of FESR	58	130	58	104	58
Maximizing exergy for NPV>0	THTG ^a	THTG	THTG	THTG	THTG
IRR > r	63	165	66	148	59
PB < 6 years	82	217	86	206	77
Maximizing NO _x reduction	137	366	155	236	140
Maximizing CO ₂ reduction	58	115	58	93	57
Maximizing CO reduction	102	266	99	174	64

^a The higher the engine size the greater the parameter, it is calculated according to the paragraph after Eq. (33C).

Table 7
The optimum engine size, benefits, initial investment and boiler size for 5 climates.

Parameters	Tehran	Ahwaz	Bandar Anzali	Chabahar	Kamyaran
$E_{nom}^{optimum}$ (kW)	83.00	211.00	88.00	161.00	78.00
FESR (%)	36.23	35.27	34.69	40.08	37.38
EXIR (%)	90.24	95.57	90.32	95.47	90.05
NPV (10^7 Rials ^a)	14.33	30.04	16.12	7.12	13.98
IRR (%)	16.60	16.37	16.67	15.44	16.61
PB (years)	5.96	6.04	5.94	6.39	5.96
NO _x Reduction ratio (%)	99.77	99.77	99.77	99.77	99.77
CO ₂ Reduction ratio (%)	45.79	43.51	44.71	46.98	46.76
CO Reduction ratio (%)	80.21	80.11	80.19	80.25	80.31
I_0 (10^7 Rials)	142.09	346.97	152.72	257.90	137.27
PVP = $100 \times NPV/I_0$	10.09	8.66	10.56	2.76	10.18
Auxiliary boiler capacity (kW)	73.74	212.50	91.62	102.33	85.44

^a 10^7 Rials = 1 Million Toman (MT) and officially 1 USD = 12260Rials.

decreasing the engine and auxiliary boiler sizes while conserving or magnifying the other benefits of the CCHP system and as a result the initial investment will decrease. These evaluations need more calculations and code generation, and are going to be done by the authors of this article. Secondly, the government benefits from using the CCHP systems, because fuel consumption is lowered, air pollution is decreased, these means saving considerable costs for the government, therefore government should support this technology economically by giving subsidies and long payback period loans to the customers to encourage them for using CCHP systems.

The cooling system of CCHP system has considerable impact on the MCSF. In this research the aim is to propose a sizing technique for the prime mover. Therefore, simply the cooling system is assumed to be an absorption chiller. However, for comprehensive optimization of equipment selection and sizing of cooling system there are four main scenarios as follow: ►To use a big absorption

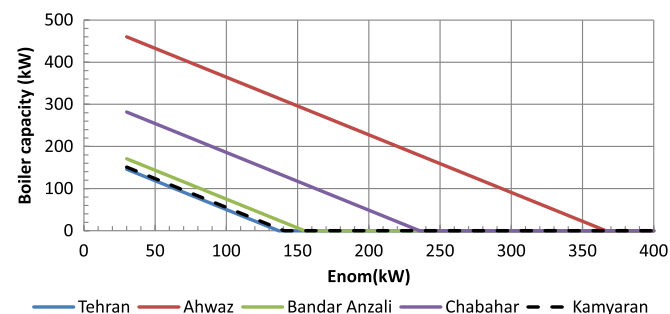


Fig. 11. Impact of engine size (E_{nom}) on the auxiliary boiler capacity for 5 climates.

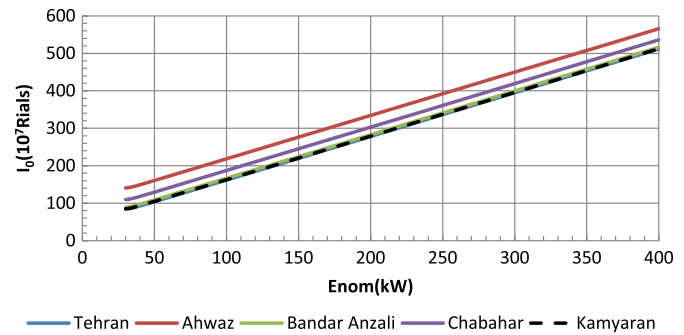


Fig. 12. Impact of engine size (E_{nom}) on the initial investment of CCHP for 5 climates.

chiller with an auxiliary boiler, or direct fire (if the recoverable heat of engine is not enough) to provide the total cooling load by a single absorption chiller. ►To use two absorption chillers. The first operates by the recovered heat from the engine and the second operates by an auxiliary boiler or direct fire for the peak time of cooling. ►To use a combination of absorption and electrical chillers, the absorption chiller uses the recovered heat and the electrical chiller uses the electricity of the engine or grid. ►To use only electrical chiller to provide the total cooling load.

The best option depends on the following parameters: Heating, cooling and electrical demand of the building, the electricity and natural gas tariffs, the economical criteria, thermodynamical evaluations and environmental evaluations. This evaluation is going to be done by the authors of this paper.

4.5. Strategy selection results

As discussed previously in the literature the classical strategies of FTL and FEL are usually used as the reference to size the prime mover. This method is weak, because only two engine sizes are tested to see if which one is better from different points of views. This research introduces three more strategies of LFEL, FEPTL, and UFTL (Table 3). According to the analyses of this research, strategy should not be considered as a constraint. Strategy is a byproduct of sizing technique. Fig. 13 shows a comparison between engine size proposed by FEL, FTL and MCSF. It shows that MCSF recommends using FEPTL for all of the climates. In this strategy, attention is paid to maximizing all of the thermodynamical and environmental sub-criteria. In addition, the project is economically designed to be profitable, safe, and have a suitable payback period. Using FTL or UFTL increases the I_0 and pollution, and decreases the FESR. In addition, using LFEL or FEL is not economical, increases pollution and decreases the FESR and EXIR. Therefore, as a result of sizing technique (MCSF) the best strategy is FEPTL. It means that the

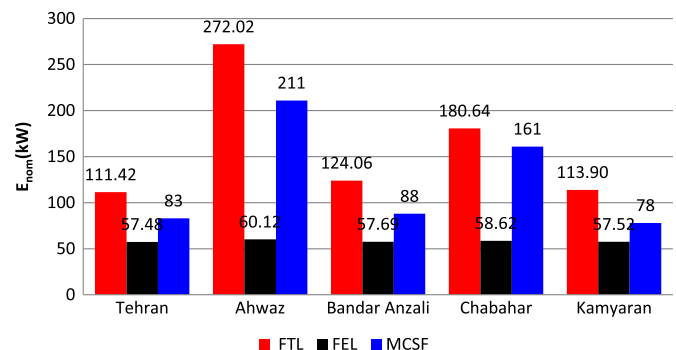


Fig. 13. Strategy proposed by the MCSF versus FTL and FEL for 5 climates.

electrical load is fully provided by the CCHP, while the thermal load is partially provided and using an auxiliary boiler is necessary at this stage. Using auxiliary boiler can be canceled by using solar heating or heat storage systems. But using these technologies need more attention and calculation which is of interest of authors and is going to be done in the future.

5. Conclusions and further outlooks

A multi criteria sizing method is introduced to size the prime mover of a CCHP system. It uses the FESR and the EXIR as the thermodynamical sub-criteria, the NPV, the IRR and the PB as the economical sub-criteria, and the NO_x , CO and CO_2 reduction ratio as the environmental sub-criteria. Also by using the AHP method, a weight is given to every criterion and sub-criterion with respect to others. The MCSF is used to size the prime mover of a residential-CCHP in five climates. The analyses show that this method is able to determine the engine size while satisfying the thermodynamical, economical, and environmental constraints and conditions. In addition, this technique is able to introduce the best strategy for every climate, while the classical methods of sizing do not have this ability. The MCSF is easily programmable and user-friendly. The CCHP proposed here can be equipped with a thermal storage system and an auxiliary solar water heater to decrease the engine and auxiliary boiler sizes, increase FESR and possibly decrease of I_0 . In addition using technologies such as photovoltaic cells and electrical storage system can magnify the profits of the CCHP system and decrease the engine size. According the results, the I_0 for some climates is high, in these cases the government economical supports is recommended to encourage customers to use CCHP units.

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